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6 STUDIES IN HYDRODYNAMIC TRACK PROPULSION.

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ABSTRACT

An investigation to improve the water propulsion performance of tracked vehicles is described. The study centers about drag measurements made in a wind tunnel and in a towing tank to investigate the effect of changing the shape and spacing of rectangular track plates.

It has been popularly believed that, due to turbulence, the first few track cleats do most of the propulsion. This investigation, however, establishes results indicating almost equal performance for all track cleats, throughout the length of the track.

Near-maximum plate thrust was obtained at spacing-to-plate-chord ratios above 6. Maximum thrust per unit length of track was obtained at a spacing-to-plate-chord ratio of approximately 1/2. Of the three rectangular-plate aspect ratios tested (2, 5, and 10), the aspect ratio of 10 gave the highest thrust per unit length.

Tests were made at plate centerline submergence-to-chord-width ratios of 2.54 and 4.57. No appreciable change in thrust was measured.

Summaries of previous studies associated with the problem of track propulsion are presented.

KEYWORDS

Hydrodynamics
Amphibians
Paddle Tracks
Propulsors

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INTRODUCTION

PURPOSE OF STUDY

The object of this study was to conduct a preliminary investigation which would provide basic design data for the optimum design of an amphibious track. With such data, a rational design of a paddle-type track for amphibious vehicles could be developed.

BACKGROUND

It is known that greater efficiency and higher water speeds can be obtained for amphibious vehicles by the introduction of auxiliary propulsive equipment. If these extra devices are not to interfere with the ground mobility of the vehicle, they must be so located that their efficiency is drastically reduced. And since they greatly complicate the vehicle system, which already has a power train for moving land propulsive devices, it would be highly advantageous to make the land propulsion devices more effective in water, eliminating the need for auxiliary equipment.

Two serious attempts have already been made in that direction, by the Davidson Laboratory of Stevens Institute of Technology. One is an attempt to analyze and improve the water propulsive efficiency of a tire.[1] The other has been to design a track which would provide improved water propulsive characteristics.[11]

Any floating wheeled vehicle can attain a certain measure of forward speed simply by rotating its tires. The action is not the same as that of a paddle wheel, since the phenomenon persists when the wheel is totally submerged. Recent research by Rymiszewski of the Land Locomotion Laboratory,[3] has demonstrated that the propulsive force appears to be a function of the vortex generated by the rotating wheel. Further research must be conducted to substantiate that hypothesis. If it proves a true one, additional studies must be carried out to determine how this new knowledge can be utilized to improve the tire's propulsive effort.

The M-59, the LVTP-5, and other tracked amphibious vehicles are capable of achieving hydrodynamic thrust by simply rotating their tracks. The use of "paddle tracks," or "hydrotracks," for water propulsion has not, however, been limited to amphibious vehicle applications. There are indications, in fact, that the use of paddle tracks may have antedated the use of paddle wheels as a means of ship propulsion.[4] At about the time World War II ended, extensive studies which included carefully controlled experiments with scale models were conducted by Sparkman & Stephens, Inc. and others[5,6] to determine the factors affecting track propulsion performance and thus to point the way toward improved hydrotrack propulsive efficiency.

More recently, studies (including model experiment work) have been conducted by the Ingersoll Kalamazoo Division of the Borg-Warner Corporation,[7,8] the U. S. Army Land Locomotion Laboratory,[9] and others. A discussion of some of these studies is presented in Appendix A.

During the period 1956-1958 the Land Locomotion Laboratory, with the assistance of Dr. W. I. E. Kamm of the Davidson Laboratory (DL), conducted some preliminary experiments on an adaptation of the cycloidal propeller.[11] Here, in the track adaptation, the paddles changed attitude as they revolved, so as to obtain maximum drag (thrust) while moving rearward and minimum drag while moving forward. This kind of propeller has long been used, with its axis vertical, to propel harbor and river tugs in Europe. On a horizontal axis it could be adapted to a track[18] or a wheel, to provide hydrodynamic thrust and lift. The basic principles of such a device was validated[9] by tests conducted at the Land Locomotion Laboratory on a simple, truncated model, which indicated that it could provide approximately 20-lb/hp thrust under stall conditions. This compares favorably with 22-lb/hp thrust for a tug boat (also operating at stall). Such a track would be a great improvement over the 1-lb/hp thrust now generated by the tracks on present amphibians.

DISCUSSION

IMMEDIATE OBJECTIVES

The study presented here was particularly directed to the acquirement of basic information needed for proper design of the track's paddle elements. Although considerable information is available concerning the lift and drag of flat plates at low angles of attack, little work has been reported for angles of attack near 90 degrees. Nor is there much information on investigations of cascaded plates at high angles of attack. This study therefore proceeded with an endeavor to obtain a better understanding of the fundamental mechanisms by which the hydrotrack develops propulsive effort, rather than with a consideration of the performance of a specific track on a specific vehicle. It is, of course, understood that the performance of any hydrotrack propulsion unit on any vehicle depends strongly on the fluid flow set up by the moving vehicle and on the interaction of the hydrotrack and the vehicle. Substantial changes in vehicle configuration for the purpose of improving hydrotrack efficiency were not contemplated.

Specifically, this study was designed to investigate the effect of the following parameters on cascaded plates at angles of attack near 90 degrees:

a. Angle of attack of individual plates
b. Plate shape
c. Plate aspect ratio
d. Plate spacing
e. Plate depth of submergence
f. Number of plates in tandem
g. Plate speed

In this report the term "drag" is used to denote the force measured on the plate while moving through the fluid (in the towing tank), or when the fluid flows past the plate (in the wind tunnel). This term "drag" would, in reality, be "thrust" that the plate would be developing if it were a cleat on a moving track.

THEORETICAL CONSIDERATIONS

Self-propulsion of any kind is necessarily a reaction phenomenon, with the propelling force derived from a pulling on or a pushing away of matter having mass. For the self-propulsion of bodies through fluids, the force needed to overcome the hydrodynamic drag is obtained by imparting momentum to a certain mass of liquid in a direction opposite to the desired direction of motion. Simple momentum considerations[12] yield expressions for the thrust and ideal propulsive efficiency of such a propulsion device:

$$\text{Thrust} = \rho Q \Delta U \tag{1}$$

$$\text{Ideal efficiency} = \frac{U_1}{U_1 + \Delta U/2} \tag{2}$$

where ρ = fluid mass density

Q = volume flow of fluid

ΔU = change in velocity of fluid

U_1 = initial velocity of fluid

These equations show that for most efficient thrust it is better to accelerate a large quantity of water a little than to accelerate a small quantity of water a great deal.

When a land vehicle is traveling on soft soil, the track linear speed is usually somewhat different from the forward speed of the vehicle. The difference is called slip, and is given by

$$S = \frac{V_t - V_v}{V_t} \tag{3}$$

where S = slip, expressed in percent

V_t = the linear velocity of the track

V_v = the linear velocity of the vehicle

This definition may also be carried over to water propulsion, provided that velocities of the fluid elements are assumed to be the same as the vehicle speed before acceleration and the same as the track speed afterwards (this will not, of course, be strictly true). Then, from Equation (2),

$$\text{Ideal efficiency} = \frac{1 - S}{1 - \frac{S}{2}} \tag{4}$$

Fluid frictional losses, mechanical losses, and losses due to the use of input energy to impart momentum to the fluid, in directions other than those opposed to the desired direction of motion, result in further reduction in propulsive efficiency, below the ideal achievable.

In a screw propeller, for instance, these additional losses are associated chiefly with skin friction on the blade surfaces and with the imparting of rotational momentum to the propeller race. In a hydrotrack, a large amount of energy is carried astern and lost in the augmented velocity of the outflow race from the propulsor. The losses associated with this energy are described by either Equation (2) or (4). Additional energy is expended in the upward components of velocity imparted around the rear sprocket and in the downward components imparted near the forward idler (Fig. 1). Another energy loss, known but not well defined, is contained in the vortices formed by water spilling over and around the edges of the grouser blades.

Perhaps the greatest losses, however, derive from the effort expended in forward acceleration of the fluid in the vicinity of the upper (return) portion of the track. It would therefore be highly advantageous if a track were to present a maximum thrust to the water during its rearward travel, but a minimum thrust during its return. Such a track was envisioned at the start of this program.

The track obtains its thrust from hydrodynamic loads placed on each track element. It would be illuminating to give some consideration to the generation of this thrust — both simplified and mainly qualitative, of necessity, since the flow in the neighborhood of a track is not yet well understood.

Let us assume that all of the thrust developed by the track is generated by the grouser elements in the lower (rearward-moving) section of the track. A sketch of this idealized configuration is given in Figure 2. Let us further assume that these are the only track elements which absorb engine power. The vehicle advancing with speed V_v has a drag coefficient C_{d_v} based on frontal area A_v. Each of the N grouser elements which are arrayed in the lower part of the track has a frontal area of A. The track speed relative to the vehicle is V_t. The drag coefficient of the grouser elements, C_d, depends on their spacing and other general arrangement features, and an average value is used for all the elements. In this elementary analysis the influence of the hull on the inflow to the tracks and of the tracks on the drag of the vehicle is disregarded. It is then possible to relate vehicle drag to the thrust output of the track.

$$C_{d_v} \frac{\rho}{2} A_v V_v^2 = N C_d \frac{\rho}{2} A \left[V_t - V_v\right]^2 \tag{5}$$

The power input to the track is given by

$$P_{in} = \frac{N C_d \frac{\rho}{2} A \left[V_t - V_v\right]^2 V_t}{550} \tag{6}$$

The useful power, or effective horsepower, is

$$P_{out} = \frac{C_{d_v} \frac{\rho}{2} A_v V_v^3}{550} \tag{7}$$

The ratio of useful power to input power, which is termed the propulsive coefficient, is given by

$$P.C. = \frac{P_{out}}{P_{in}} = \frac{V_v}{V_t} = (1 - S) \tag{8}$$

The above analysis, which ignores the large power absorption involved in pulling the other elements of the track and the reduction in thrust which may be associated with the upper, or return, portion of the track, nevertheless reveals some significant features of hydrotrack propulsion. Efficient hydrotrack propulsive devices are associated with low track slip. This, in turn, is associated with large grouser frontal areas and high values of the product NC_d .

A sample calculation of the propulsive coefficient described by Equation (8) can be carried out by making certain additional simplifications. Such a calculation can be expected to result in a quite over-optimistic prediction. It may, however, indicate an "upper bound" on the efficiency that can be expected from a hydrotrack device. Numerical values used in this calculation are based on approximate dimensions for the LVTP-5 and certain data obtained in tests conducted at the Davidson Laboratory.

Let C_{d_v} = 0.45 (See Van Dyck[13])

A_v = 62.2 ft^2

N = 100

C_d = 0.3 (data presented in section on tests of plates in tandem)

A = 0.28 ft^2

ρ = 1.99 $lb\text{-}sec^2/ft^4$

Then, from Equations (5), (6), (7), and (8), the propulsive coefficient is about 0.35, and a minimum power input to the water of approximately 100 hp is required to achieve 6 mph. In operation, the LVTP-5 uses about 850 hp to achieve this speed, with a value of $V_v/V_t = 0.43$.

It is evident, as expected, that the actual track does not perform as efficiently as the idealized lower portion of the track. The value for track slip is rather close to the value for the idealized track, but this is purely a coincidence. The difference in power required to achieve 6-mph speed, for the idealized and for the actual track, is extremely large, and improvements in hydrotrack efficiency can be expected to result in substantial pay-offs. Some of the power developed is of course used merely to actuate the mechanical system of gears, shafts, and track elements at a speed corresponding to 14 mph on land, but it is evident that an enormous amount of power is being expended wastefully in the water.

In comparisons of the effectiveness of different kinds of propulsive devices at zero speed of advance, the pounds-of-force-per-horsepower-delivered index is often used as a merit figure. However, this comparison is not adequate for general discussions, since almost any desired merit figure can be achieved, depending on the size of the device used and the power delivered. Consequently, when comparing <u>different</u> <u>kinds</u> of propulsive devices, the pounds of force per horsepower delivered must be associated with a particular size and with delivered power. A weight and space analysis of various propulsive devices is thus intimately involved with a propulsive-effectiveness analysis.

In order to clarify this issue somewhat further, let us examine the case of a screw propeller, which experience has indicated to be one of the best means for generating propulsive force in water. The expression for pounds of thrust per horsepower of a propeller is

$$T/hp = (550^2 \rho)^{1/3} \left(\frac{K_t}{K_q^{2/3}}\right) \left(\frac{hp}{D^2}\right)^{-1/3} \quad \text{(A1)}$$

where D = propeller diameter

ρ = fluid density

T = propeller thrust

and the thrust coefficient, K_t, and torque coefficient, K_q, are defined by the equations

$$T = K_t \rho n^2 D^4$$

$$Q = K_q \rho n^2 D^5$$

where Q = shaft torque

n = shaft speed in rps

The importance of power loading, hp/D^2, and of the non-dimensional thrust and torque coefficients, is clearly revealed in this formulation. A rule of thumb for tug boats of usual design characteristics holds that one long ton of pull can be exerted with 100 horsepower.

As noted above, little theory exists for flow about flat plates at angles of attack near 90 degrees. There is much in the literature, however, which indicates that the drag coefficient of a rectangular flat plate normal to the fluid flow is constant at Reynolds numbers above 1000 and approximately equal to 1.17, regardless of aspect ratio.

Riabouchinsky developed a theory of fluid flow about two plates in tandem.[14] His theory, however, is quite at variance with measured data. Studies[15] also have shown that cupped plates, with the concaved sections facing the stream flow, have up to 20-percent greater drag than flat plates. A review of pertinent literature relating to the drag of flat plates is presented in Appendix B.

TESTS

PROGRAM

In accordance with the objective (to obtain data for the design of a future variable-pitch paddle track), a test program was developed which would measure the drag on tandem plates in fluid flow at angles of attack near 90 degrees, with variations in Reynolds number, plate aspect ratio, plate spacing, depth of submergence, and number of plates in tandem. It was decided to conduct part of the program in the Davidson Laboratory wind tunnel and part in the Davidson Laboratory Towing Tank 3. Smoke traces could be observed, and pressure probe measurements more easily made, in the wind tunnel, while near-surface effects, and tandem arrangements of more than five plates, could only be conducted in the towing tank. A description of these facilities is contained in a Davidson Laboratory publication.[16]

MODEL DESCRIPTIONS

The plate models were all made of 1/4-inch-thick aluminum plates with a projected area of 14.4 square inches. The edges were sharp, with a 45-degree bevel from the forward face which gave the following face a smaller area. Plate sizes investigated were:

Breadth (in.)	Chord (in.)	Aspect Ratio	Frontal Area ($in.^2$)
12	1.2	10	14.4
8.5	1.7	5	14.4
5.37	2.69	2	14.4

For wind-tunnel tests these plates were mounted on streamlined struts (see Fig. 3). The plate to be measured was mounted on a strut connected to a balance which measured lift and drag. This strut was shrouded from the impinging wind stream by a streamlined cover. Other (interference) plates were mounted to the tunnel floor (also on streamlined struts) directly upstream and downstream from the plate being measured.

For tests in the towing tank, the plate on which the drag was measured was connected to the balance with a streamlined strut which was not shrouded (see Fig. 4). The measured drag was corrected to account for the strut drag. A single plate was mounted behind (downstream of) the measured plate and attached to a separate strut not connected to the balance. The plates mounted ahead of the measured plate were mounted on a 5/16-inch-diameter stringer which skewered the plates. The stringer was supported at two or three places by streamlined struts. For the towing-tank tests, many more plates were arranged in tandem than for the wind-tunnel tests, but only plates with an aspect ratio of 2 were used in the tank tests.

WIND-TUNNEL TEST RESULTS

Two series of experiments were performed in the DL wind tunnel.

The first series consisted of smoke-visualization experiments for flows about a single plate and two tandem plates, at various angles of attack. These tests were very much of a preliminary nature, yielding no quantitative information. The general quality of the photographic data is rather poor due to difficulties with lighting and smoke. Nevertheless, by using the photographs in conjunction with the results of direct observation, it is possible to draw the following general conclusions:

(1) A definite stagnation bubble was formed behind a single plate of a length roughly equal to 4 chord lengths at a 90-degree angle of attack and 2.5 projected chord lengths at a 45-degree angle of attack.

(2) If the afterplate in a tandem two-plate arrangement was placed approximately 7 chord lengths or more aft of the foreplate, the effect of the foreplate on the inflow to the after one appeared to be negligible. This fact is regarded as potentially of considerable importance with respect to track-cleat spacing.

The second series of wind-tunnel tests consisted of measurements of the aerodynamic drag acting on plates of aspect ratios 2, 5, and 10, at a 90-degree angle of attack, under various conditions of interference due to the presence of similar plates in tandem upstream and/or downstream from the measured plate. The chief results are as follows:

(1) For the case of a single plate, the drag coefficient based on frontal area was approximately 1.4, and was practically independent of aspect ratio within the range of 2 to 10. This value is somewhat higher than the value (about 1.17) obtained in earlier experiments.[15,17] The discrepancy is probably due to interference from the support strut, difference in the construction of plates, and/or tunnel-blockage effects.

(2) The effect of a downstream interference plate on the drag of the measured plate upstream is small but noticeable, especially at close spacings. No measurable difference was found in changing from one to two downstream plates.

(3) The influence of upstream interference plates is great. The influence varies significantly with the number of upstream plates and their spacings. At close spacings, with one or two upstream plates, negative drag is created due to the wake formation of the stagnation bubble mentioned above (Figs. 5, 6, and 7). As the number of upstream plates increases, this negative effect disappears.

As plate spacing increases, the drag on the measured plate also increases, approaching the value for a single plate with no upstream interference. Of particular interest is the fact that the fourth and fifth plates in tandem (with three and four plates upstream) have approximately the same drag. This is contrary to the widely held belief that only the leading few plates contribute significantly to the hydrodynamic thrust.

An important consideration, however, is the drag per unit length of track, since a given track design has only a limited length of track. Such a comparison is presented in Figure 8, which shows that with five plates in tandem, the drag per unit length of track increases with aspect ratio up to an aspect ratio of 10. The optimum spacing-to-chord ratio is not apparent from the data.

(4) Within the range of Reynolds numbers tested (from 10^4 to 6×10^4), there is no appreciable variation in drag coefficient. This is consistent with accepted theory, which states that, in clearly separated flows such as this, the flow characteristics are independent of Reynolds number grater than 10^3.

(5) Tests on tandemly arranged plates, at angles of attack equal to 75, 60, and 45 degrees to the fluid flow, indicate similar effects on both lift and drag.

TOWING-TANK TEST RESULTS

Tests were conducted in DL Towing Tank 3 to measure the drag acting on a flat plate of aspect ratio 2 (with the long axis horizontal) at a 90-degree angle of attack, mounted in tandem with other plates. These tests were intended to complement the earlier tests conducted in the wind tunnel and to provide certain new data. The primary reasons for conducting tests in the towing tank, as well as in the wind tunnel, were:

(1) Because of the limited length of the wind-tunnel test section, only a limited number of plates (5) could be placed in tandem.

(2) The measured drag coefficient on a single plate in the wind tunnel was found to be higher than the generally accepted value. This may be due to flow blockage in the wind tunnel, to inaccuracies in the wind-speed measurement, or to other unknown effects. It was hoped that the towing-tank tests might shed some light on the reasons for these discrepancies.

(3) The influence of the free surface and the depth of submergence can be investigated only in the towing tank.

Tests of a single plate and of five, eight, and ten plates in tandem were conducted in the towing-tank. Only the aspect ratio of 2 was tested, since this is close to that presently employed in amphibious track grousers.

The results of the towing-tank tests gave a drag coefficient of 1.11, about 4-percent lower than the usually accepted value of 1.17 and 20-percent lower than the value of 1.4 obtained in the wind tunnel. There may be a slight reduction in drag on the plate, due to the stringer-mounting configuration which fills out part of the space of the wake.[15] Other possible explanations of the discrepancies include a strut-plate interference and free-surface effects. Since the same strut-plate configuration was used for both wind-tunnel and towing-tank tests, any discrepancy due to the strut-mounting should be the same. The measured discrepancies, however, are distinctly different. The ratio of the projected area of the plate to the cross-section area of the closed-jet wind tunnel is about 0.02, which is rather high. It must therefore be assumed that the discrepancies are a result of a combination of the blockage effects and inaccuracies in air-speed measurements.

Measurements were made of plate drag at two different depths of submergence, viz., the submergence of plate centerline to plate chord lengths of 4.57 and 2.54. No measured drag difference was observed; hence it must be concluded that there are no free-surface effects within this range (Figs. 9 and 10).

Results of tests conducted with five, eight, and ten plates in tandem, for the deep-draft submergence of 4.57 chords, are given in the form of drag coefficient against spacing/chord, in Figure 9. Drag coefficients versus spacing/chord ratio for tests of five plates in tandem, at a submergence of 2.54 chords, are shown in Figure 10.

Figure 9 shows that the results of tests with eight and ten plates in tandem are within the scatter of data. Hence it may be concluded that the two curves lie on top of each other and that, consequently, plots of tests with more than ten plates in tandem should do so.

Figure 10 shows that the scatter of the data is rather great. An outrigger stiffening arrangement, connecting the monorail carriage to a dolly which rolls along the tank side, had to be fitted to provide sufficient torsional rigidity about the tank-rail axis, to avoid severe hydrodynamically induced vibration. Without this stiffening, strong induced vibration occurred with large amplitudes of oscillation. This gave rise to very large drags. The vibration of the system was effectively eliminated by the attachment of the outrigger, but some smaller hydrodynamically induced oscillations of the drag plate might have been triggered during some of the test runs. The nature of the flow, and consequently the drag, for such strongly separated flows is highly unsteady in any case, and the average value of the drag may change with time even though the Reynolds number for the flow is considerably higher than that corresponding to what is usually considered critical. It is felt that the variations in measured drag coefficient are real and flow-associated, not a consequence of spurious measurements or failure to follow a consistent technique in obtaining measurements.

The information in Figure 9 has been replotted in Figure 11, in the form of $C_D/\frac{s}{c}$ versus s/c , to yield a plot of drag coefficient per unit length of track. The optimum plate spacing is near 0.5 since, although data for very low spacings were not obtained, it is evident from an inspection of Figures 10, 11, and 12 that the curve of $C_D/\frac{s}{c}$ is approaching a flat "plateau" for low values of s/c . In any case, requirements for practical track configurations rule out smaller spacings, with which, at most, a very small improvement in drag performance could be achieved.

DISCUSSION OF RESULTS

In a track adaptation of the variable-pitch propulsion principles, grouser attitude is controlled in such a way that the grousers are angled to develop maximum thrust when traveling rearward and minimum drag when moving forward. This offers significant promise, from the hydrodynamic point of view, for improving propulsive performance without introducing ancillary propulsion systems.

As a result of the tests conducted in this study, it is now evident that the grouser track elements should be spaced rather closely (near 1/2 chord width). It is apparent, also, that in accordance with simplified theoretical considerations the projected profile area of the elements in the lower (working) section of the track should be as large as possible, while the profile of the upper portion of the track should be so controlled that the projected frontal area (and consequently the drag on the grouser elements) is as small as possible. In view of the latter requirement, it would appear that a flat, or nearly flat, grouser element should be used, even though cupped elements may have higher drag coefficient.[15]

During the initial phases of this program it was not clear whether the hydrodynamic track elements should be angled so as to develop lifting force or pitching moments on the vehicle in addition to thrust. It was felt that perhaps, if one or both were so developed, some improvements in vehicle drag or in other phases of performance might result. Tests conducted at DL by R. Van Dyck,[13] however, show that reducing the immersed volume of "normal" amphibious vehicles has practically no significant effect on the drag. There is, however, some effect in changing trim angle, to create reserve freeboard and increase the speed at which vehicle swamping (with the attendant large drag increases) occurs. Hence it is felt that the hydrotrack propulsive device should not be called on to develop vertical lifting forces, but should be designed to provide the maximum possible thrust force for the power available. Such a configuration should also provide some degree of bow-lifting torque and, consequently, additional bow freeboard.

In the field of ship hydrodynamics, resistance and propulsion problems have been handled quite successfully by carrying out resistance tests and propeller-characteristic tests separately, and making a final test to determine the propeller-hull interaction effects. By using suitably clever "bookkeeping" methods for interpreting the resulting data, certain numerical factors can be deduced which, together with a reasonable backlog of previous test information, can indicate whether or not the ship and/or the propellers under consideration are good for the intended service. From this sort of information, one can obtain considerable insight into where and how improvements in the propulsive qualities of the vessel can best be achieved, e.g., in the propeller, in the hull form, or in the propeller aperture.

For the propulsion of amphibious vehicles with paddle tracks, the interaction of the hull form and the propulsive device is a more complicated phenomenon. Furthermore, the level of technical effort directed toward the improvement of water propulsion qualities of hydrodynamic-track propellers does not compare with that directed, over the years, toward the betterment of ship-propulsion qualities. It is therefore important to devise test techniques for track-propelled vehicles which, when used in conjunction with a suitable method of analysis, will yield useful information on the performance of the various components of the vehicle.

Even now, standard bookkeeping terminology is not employed in hydrodynamic-track propulsion investigations. Some investigators[8] measure vehicle resistance with the tracks moving so that the track velocity on the lower part of the track is equal to the vehicle speed of advance. The propulsive coefficient in this case is given by the ratio of the power derived from the product of speed times this kind of measured drag to the power delivered. Others[5] measure vehicle resistance with a locked track, and use this resistance in the propulsive-coefficient calculations. Still others[13] measure drag with smoothed-out tracks of sheet metal — but with wheels, sprockets, etc., attached. To the writers' knowledge, no drag tests have been reported in which all tracks and wheels and drive sprockets have been removed. Hecker and Nuttall[5] do give some data on drawbar pull for various speeds, with track speed varied as a parameter.

During the course of this study, personnel of the Davidson Laboratory visited the U. S. Marine Corps Landing Craft Development Center at Quantico, Virginia and observed an LVTP-5 during water-borne operations. The following significant observations were made:

(1) The water flow around the LVTP-5 at operational speeds is highly agitated. This results in entrainment of small (significant size: approximately 1/16 in. to 1/8 in. diameter) air bubbles in the flow, at least near the water surface along the sides and in the wake of the vehicle.

(2) These turbulent flow conditions are due primarily to the poor hull form of the vehicle but may be aggravated by the operation of the track propulsor. This last inference is made on the basis of starting tests in which the strong eddy down the side of the model, just aft of the forward shoulder, appeared to build up before the vehicle had attained enough speed to make the shoulder wave at the same location strong enough to yield the observed deep trough.

(3) Power absorption of the track in water is higher than on land. Land speed is 30 mph at roughly 600 hp; water speed is about 6 mph at roughly 850 hp, with a track speed corresponding to 14 mph. This is highly significant, since it had been assumed that insufficient power was being transferred to the water. On the contrary, the track creates considerable thrust, but much of it is not directed into forward propulsion of the vehicle.

(4) It is felt that neither cavitation nor ventilation occurs on the track grousers, mainly because the speed of the track through the water is not very high. The effects of air entrainment, or two-phase flow, are not known. In fact, it is not known whether the small bubbles of air observed near the surface of the water are present in the flow by the tracks.

CONCLUSIONS

1. For optimum thrust per unit length of track, a spacing/chord ratio of about 1/2 should be employed.
2. A maximum area should be presented to the fluid during the rearward (thrust) cycle and a minimum area during the forward (return) cycle. A flat plate which changes attitude with track position is therefore highly desirable.
3. It is not desirable to angle the track cleats to provide lift while also providing thrust.
4. For equal areas, a grouser aspect ratio of 10 will provide more thrust than aspect ratios of 2 or 5.
5. All track elements of a long track provide approximately the same thrust; hence a long track is desirable, providing the engine has enough power to utilize the thrust obtainable.
6. No change in thrust is apparent with change in track submergence.
7. Since considerable drag is already generated by present amphibious track designs, it appears more important to direct that thrust than to design a track which generates more thrust.

RECOMMENDATIONS

It is recommended that the data presented in this report be used to design, build, and test a model track with variable-pitch grousers, to determine actual track performance.

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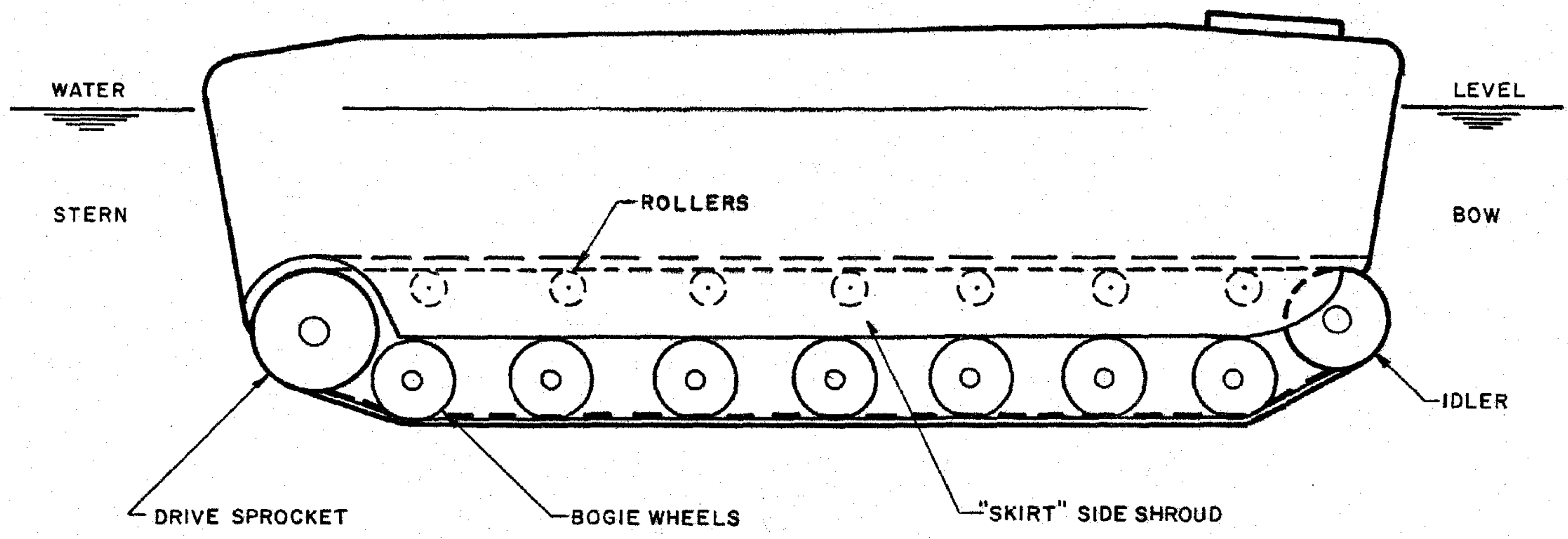


FIGURE I. SKETCH OF TRACK CONFIGURATION, LABELLING SOME OF COMPONENTS, FOR COMPLETELY SUBMERGED TRACK SYSTEM

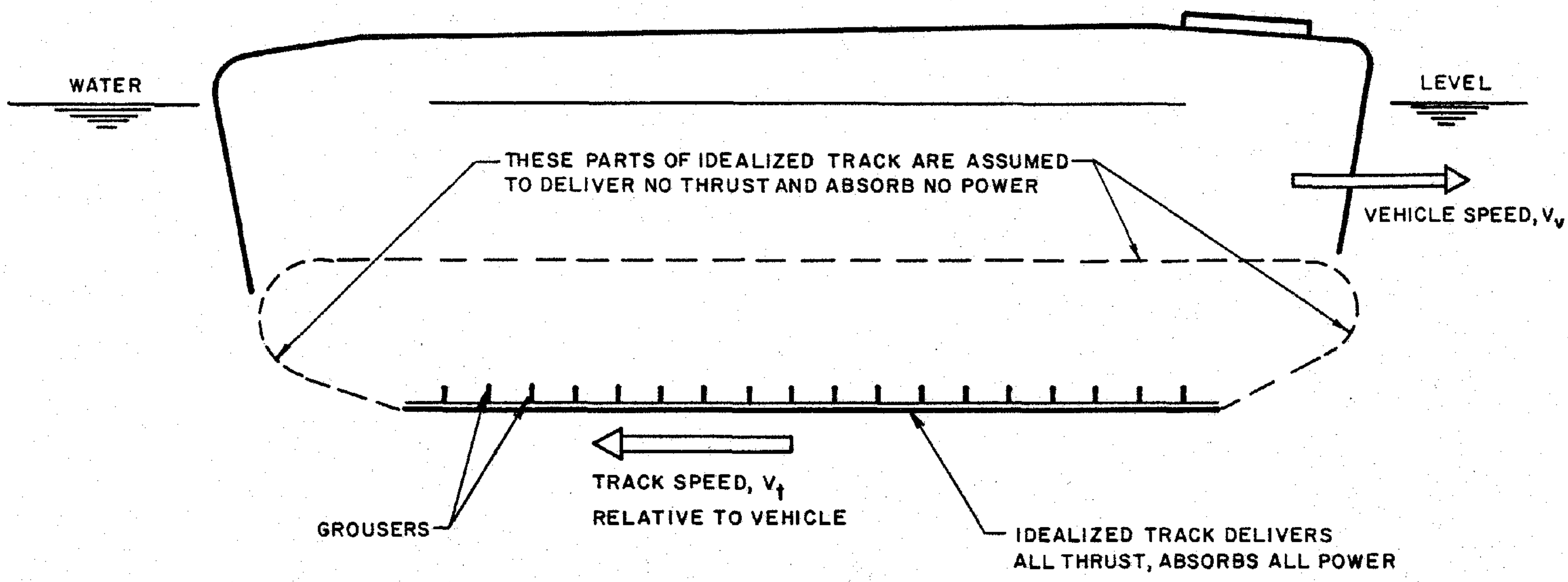


FIGURE 2. SKETCH OF IDEALIZED TRACK CONFIGURATION

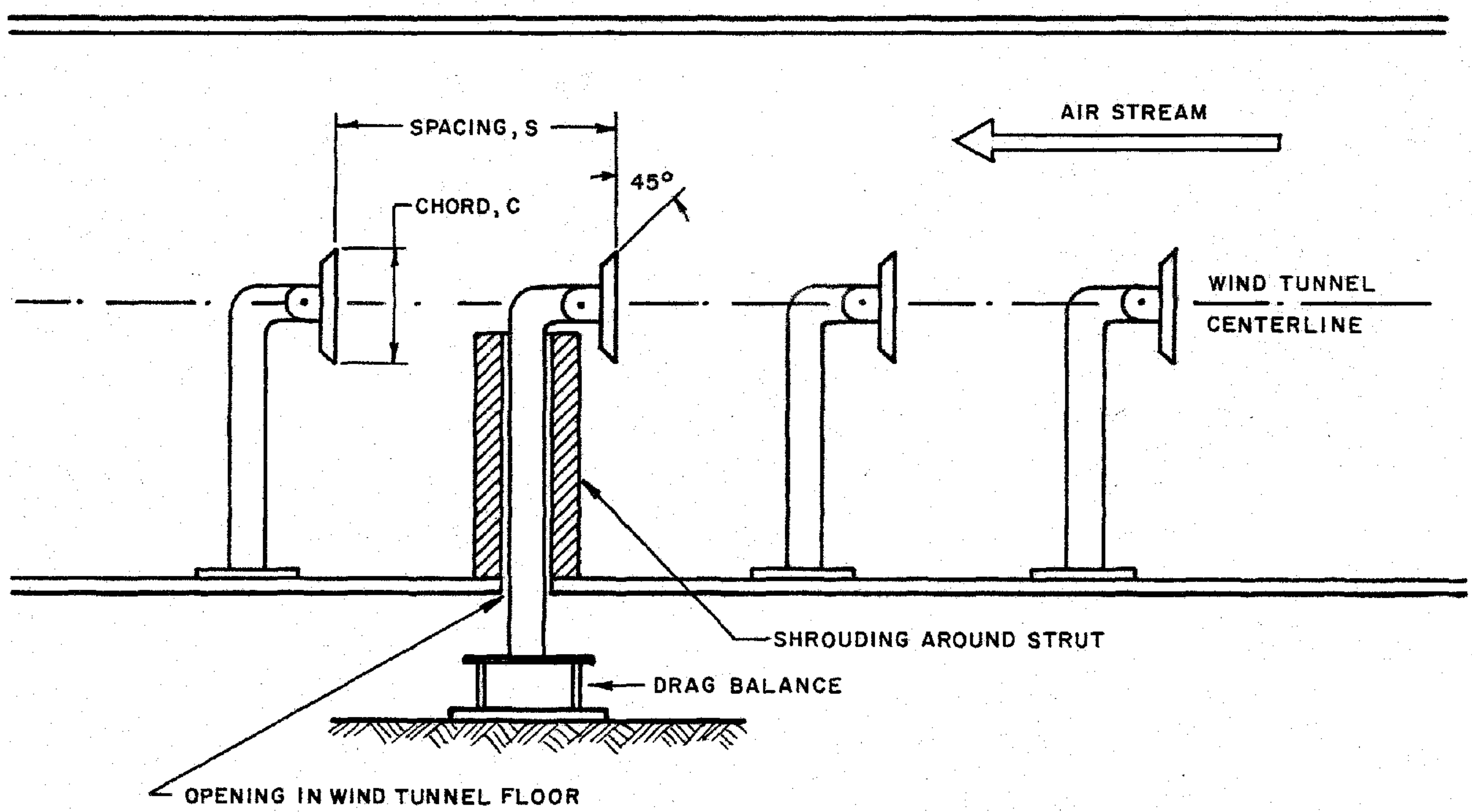
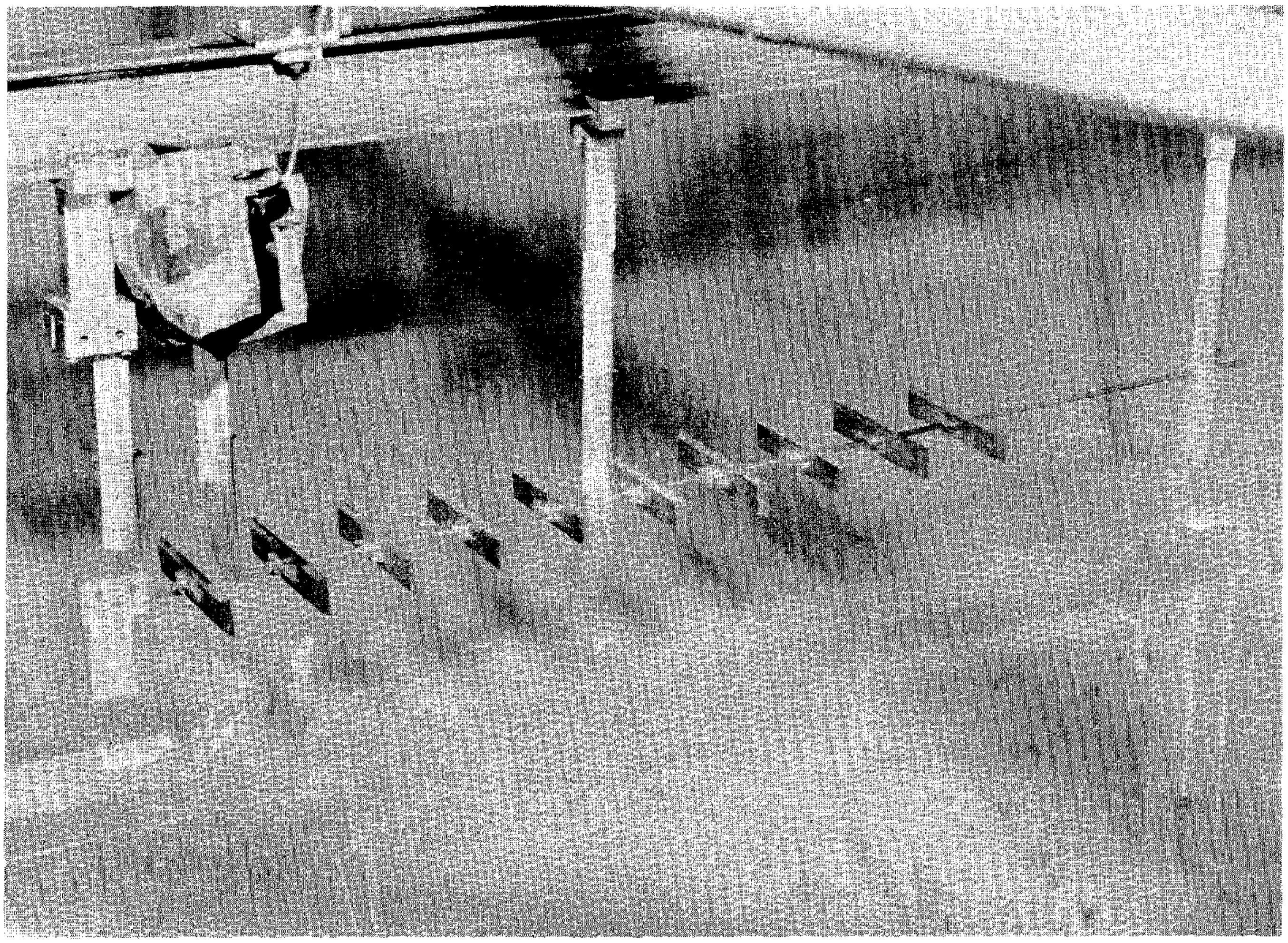


FIGURE 3. SCHEMATIC OF WIND TUNNEL TEST SET UP FOR MEASURING DRAG OF PLATES IN TANDEM



FLAT PLATES IN TANDEM MOUNTED IN POSITION
FOR TESTS IN DAVIDSON LABORATORY TANK NO. 3

FIGURE 4

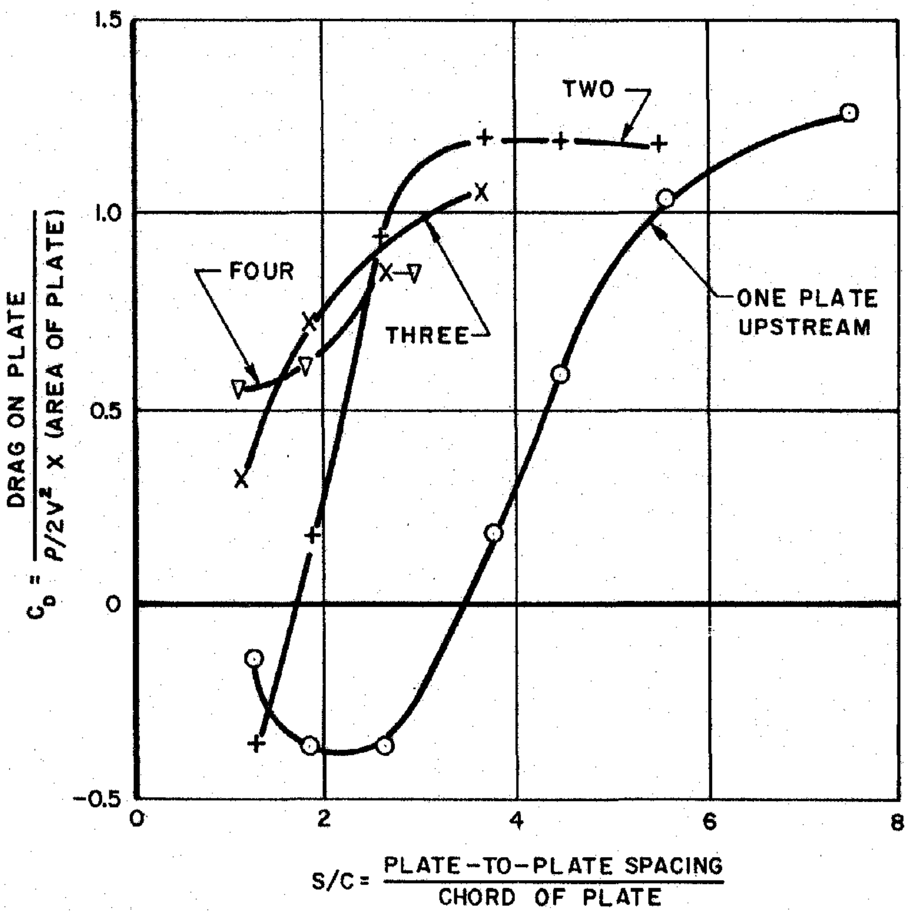


FIGURE 5. DRAG MEASURED ON LAST PLATE IN CONFIGURATION
ASPECT RATIO = 2 WIND TUNNEL TESTS

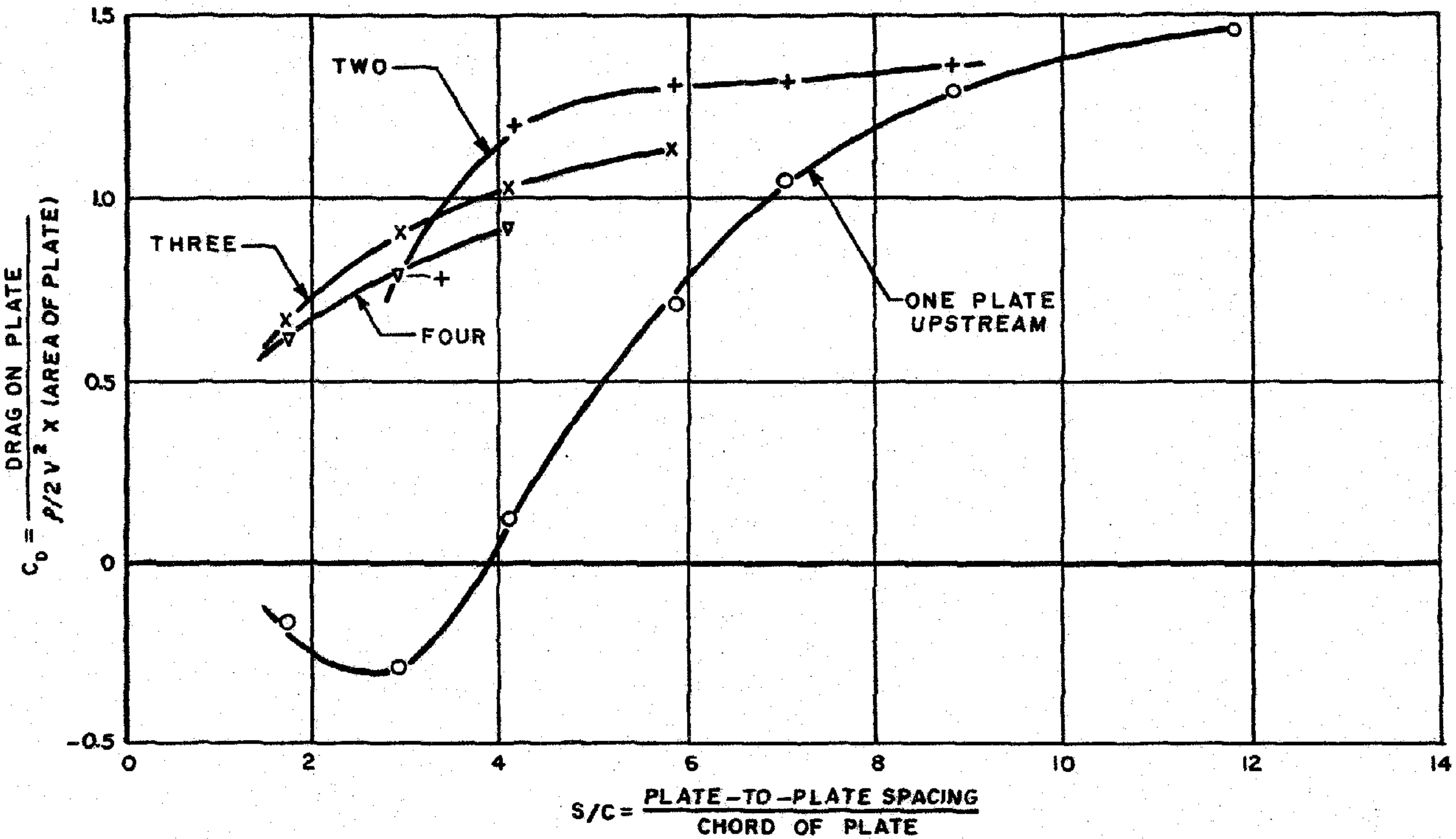


FIGURE 6. DRAG MEASURED ON LAST PLATE IN CONFIGURATION
ASPECT RATIO = 5 WIND TUNNEL TESTS

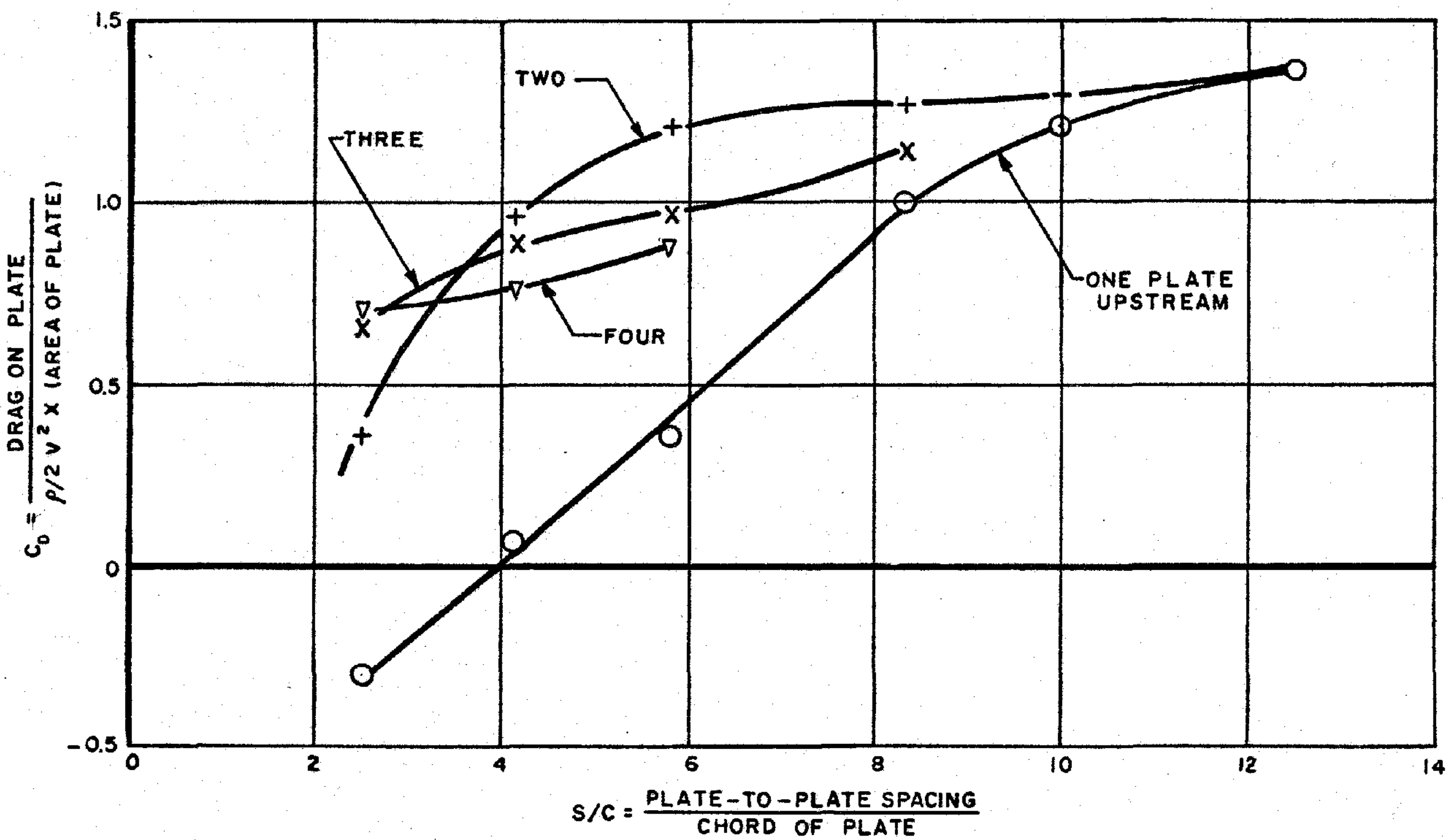


FIGURE 7. DRAG MEASURED ON LAST PLATE IN CONFIGURATION
ASPECT RATIO = 10 WIND TUNNEL TESTS

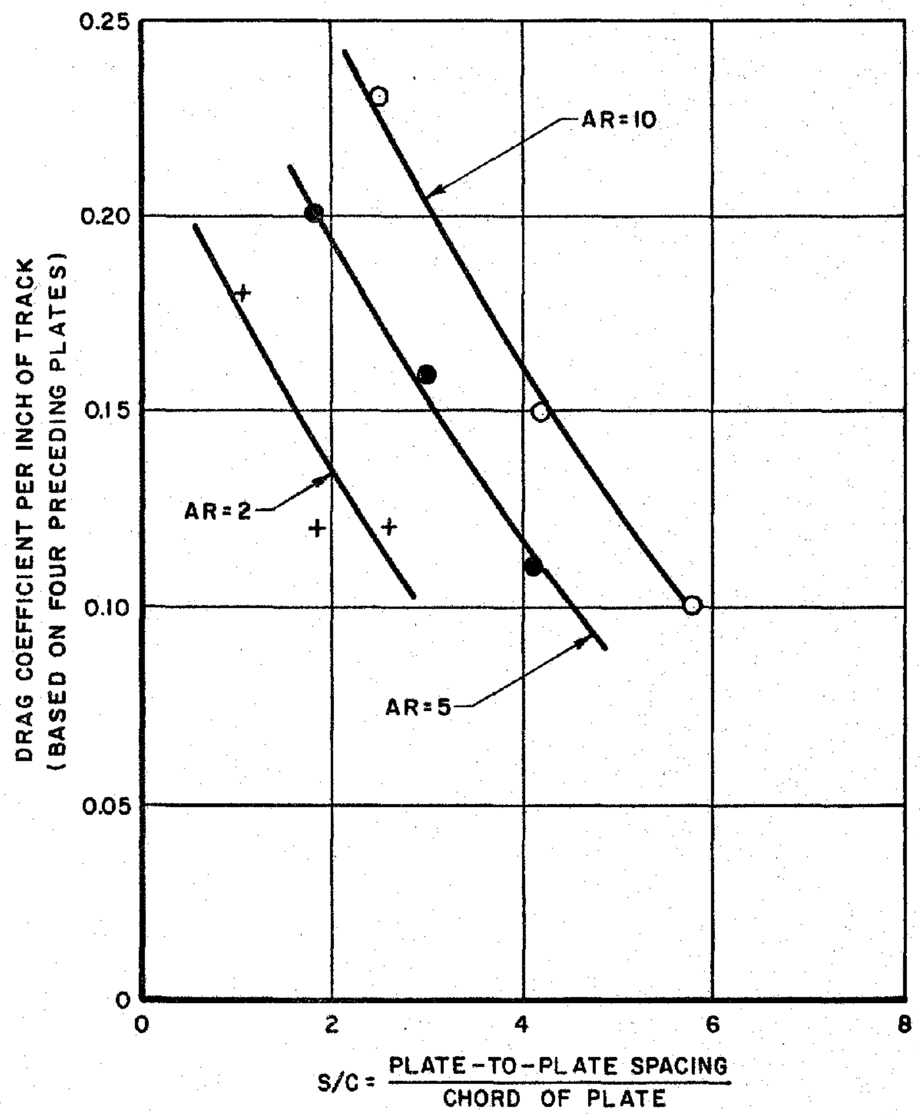


FIGURE 8. WIND TUNNEL TESTS ON DRAG OF FLAT PLATES IN TANDEM (DRAG-PER-UNIT-LENGTH OF TRACK)

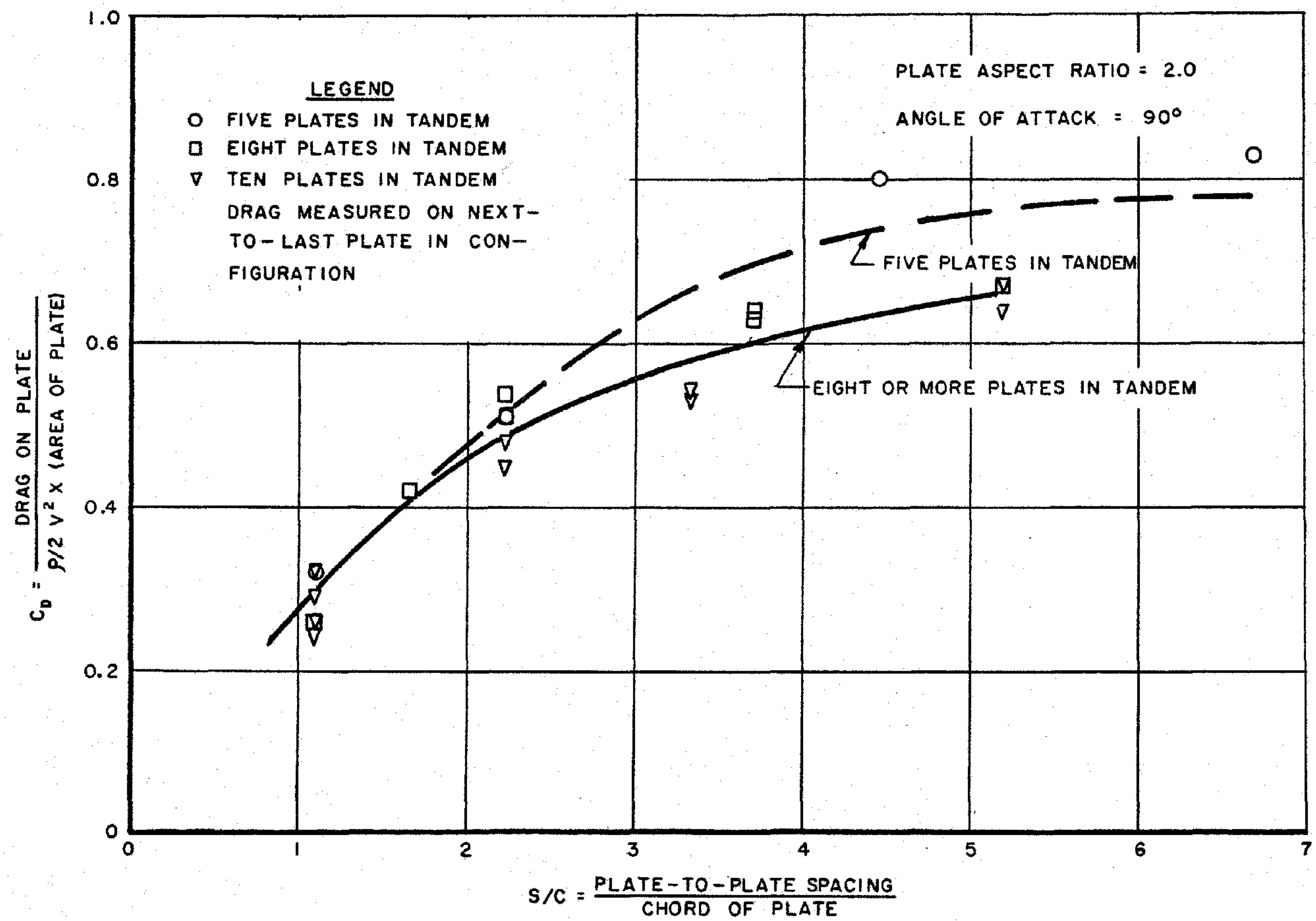


FIGURE 9. TOWING TANK TESTS ON DRAG OF FLAT PLATES IN TANDEM

$$\frac{\text{SUBMERGENCE TO PLATE } \mathrm{℄}}{\text{CHORD OF PLATE}} = 4.57$$

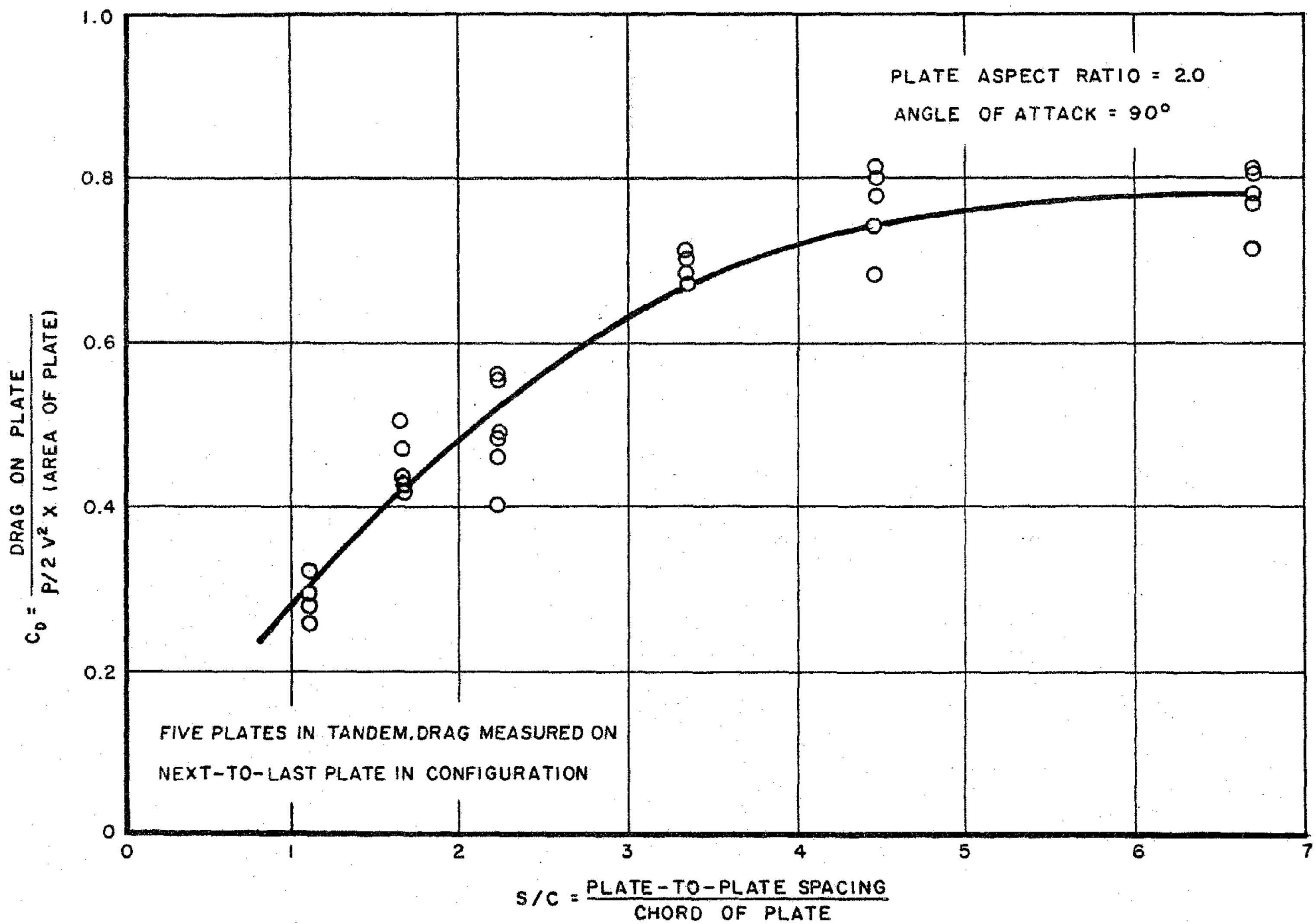


FIGURE 10. TOWING TANK TESTS ON DRAG OF FLAT PLATES IN TANDEM

$$\frac{\text{SUBMERGENCE TO PLATE } \mathbb{C}}{\text{CHORD OF PLATE}} = 2.54$$

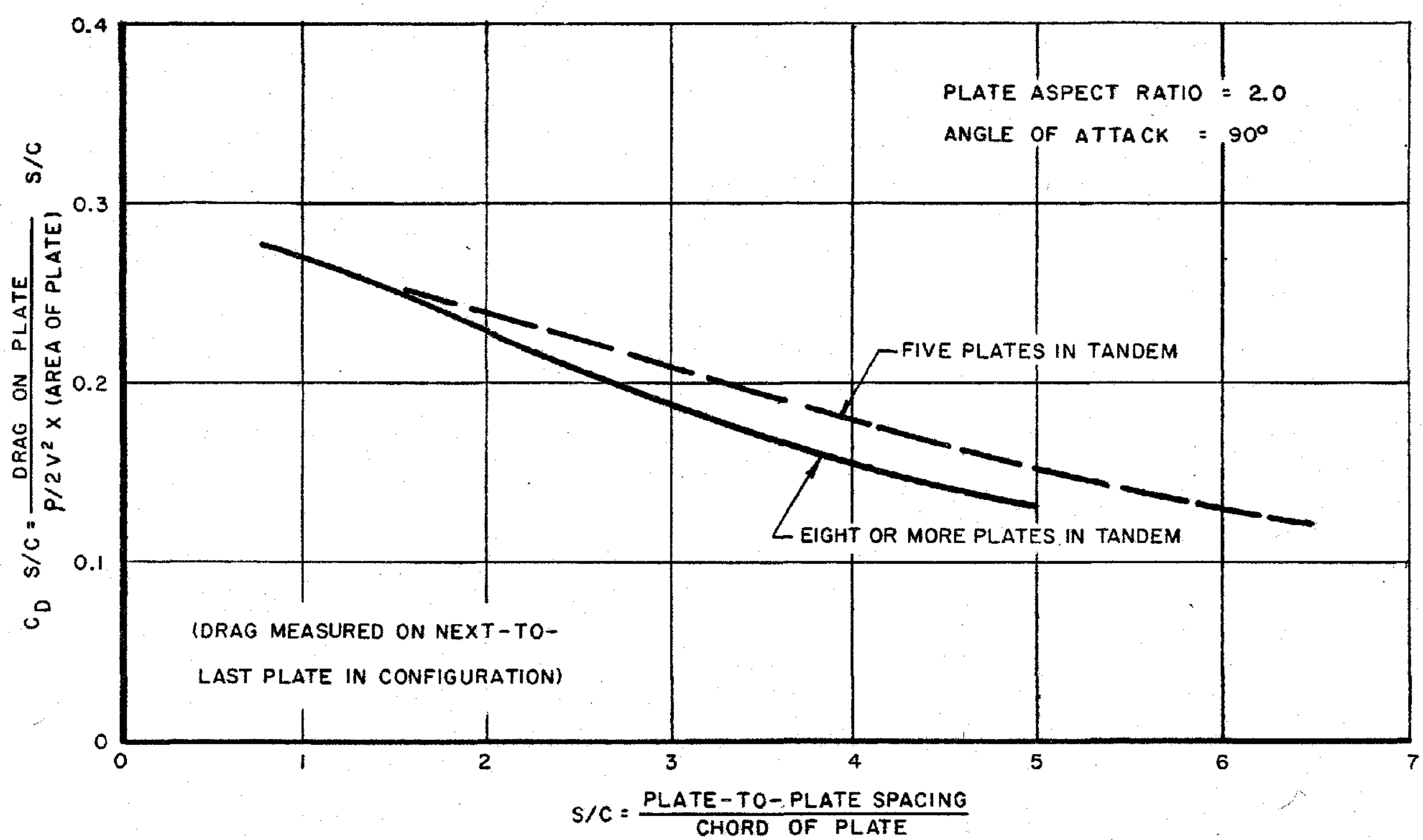


FIGURE 11. TOWING-TANK TESTS ON DRAG OF FLAT PLATES IN TANDEM (DRAG PER UNIT LENGTH OF TRACK)

APPENDIX A

EARLIER MODEL TESTS ASSOCIATED WITH HYDROTRACK PROPELLED VEHICLES

The results of tests conducted with scale models of hydrotrack-driven vehicles in water are reported in References A-1, A-2, A-3, A-5, and A-6. The effects on power requirements of changes in vehicle configuration, track configuration, and details of the vehicle around the track (including fenders and cover plates) were studied.

TESTS REPORTED BY HECKER AND NUTTALL (REF. A-1)

Hecker and Nuttall reported work carried out at Sparkman & Stephens, Inc. The model experimental work was conducted in the facilities of the Experimental Towing Tank (now the Davidson Laboratory) of Stevens Institute. (Actually, the model-test work was initiated at Webb Institute of Naval Architecture,[A-6] as part of a senior thesis project.) A basic amphibious vehicle, called the "ARK" (T-24), was modelled at approximately 1/4-scale. The purpose of these tests was to investigate particular factors involved in track propulsion, with the return track submerged, and to establish principles and methods applicable to future design.

Tests included examination of —

(1) Variations in the clearance between the underside of the sponson and the top of the return track.

(2) Five different kinds of "bow blocks," or devices placed at the forward end of the return track for the purpose of changing the direction of the water leaving the return track.

(3) Track "skirts" or sheet-metal extensions of the hull, outboard of the track — forming, with the sponson and hull, a tunnel in which the return track operates.

(4) Various lengths of stern scoops (to form a channel behind the stern sprocket, with constant clearance from track to scoop).

(5) Stern "wings" which strip water off the return track just forward of the stern sprocket and turn it 180-degrees outboard and astern.

(6) Methods of "stripping" the water from the track at the stern sprocket by means of a vertical plate tangent to the track.

(7) Various sizes and arrangements of holes in the skirt along the line of the return-track tunnel, above and below the track and at several stations along the track.

(8) Variations in track submergence.

(9) Ten different kinds of tracks, including a plain rubberized-fabric band track, a block track, and tracks with many different kinds of grousers.

Measurements were taken of power input to the track, track speed, model speed, and model drawbar pull or resistance. Power data were corrected for tare friction by running the model in air. The greatest amount of data was obtained for zero model speed where the measured drawbar pull was taken to be a measure of the hydraulic efficiency.

The most important general conclusions reached in these tests were:

(1) Clearance between track and sponson is important with normal grouser tracks and with a well-encased return-track tunnel. Minimum clearance is desirable.

(2) The bow block is the most important single shrouding item; therefore, the best possible should be provided in every design. Power required for a given drawbar pull can be reduced by 50 percent or more with a properly designed bow block. The bow block should discharge water smoothly, back into the track system rather than outboard, and should turn the water through as large an angle from dead ahead as possible.

(3) Track skirts are second in importance only to bow blocks, for vehicles with submerged return tracks. They should

be long enough to form a complete tunnel for the return track.

(4) Stern scoops with enclosed sides are helpful, particularly if good bow blocks are used.

(5) Stern stripping is not desirable.

(6) Tests on track-configuration changes revealed that

(a) Grousers may be too closely spaced.

(b) Formed grousers, with a double chevron, or "W" shape, with the open end (top) of the "W" facing the direction of track motion, are more effective than straight grousers by about 35 percent when the ratio of grouser-spacing to height is 8.

(7) The best propulsive coefficient measured in the self-propelled tests was about 8 percent.

(8) Drawbar-pull tests are a good criterion of the relative effectiveness of various track-vehicle configurations. This conclusion is somewhat analagous to the towboat situation, where bollard-pull tests give a good indication of towing ability.

Full-scale tests were also conducted, with a lesser range of variables covered, and full-size model correlation attempted. Comparisons indicate, where comparable data are available, that model and full-scale test results agree, at least approximately, in all cases — and quite well in some cases.

TESTS REPORTED BY FOLSOM AND HOWE (REF. A-2)

Folsom and Howe reported model-test work on the propulsion of amphibious craft, conducted by them at the University of California, Berkeley, during World War II. The three models used were approximately 3/16 of full-scale. In these tests, the measurements made by Hecker and Nuttall were taken; in addition, the running trim angle was measured.

The University of California tests involved variations in hull shape (bow and stern), grouser shape, and the arrangements of fenders or cover plates over the sides and ends of the track path. The general conclusions were:

(1) For grouser tracks considered to be good, the slip of the grousers relative to the water was between 50 and 56 percent.

(2) The drag coefficient for the grousers, based on projected area and track speed, was approximately 0.8.

(3) In all cases the trim under way was different from the trim with power shut off, the bow tending to rise with the application of power. This effect is in keeping with the reaction due to the motion of the track grousers.

(4) The performance of grousers under way is <u>not</u> directly related to static pull data, due, apparently, to the effect of hull shape on the flow of water into the grousers. The hull shape underwater should be such as to conduct water readily to the inner sides of the lower grouser path. (This conclusion is contrary to that found by Hecker and Nuttall. The correctness of either conclusion evidently depends on the relative loading, or slip, or some degree of digression from bollard-pull operating conditions.)

TESTS REPORTED BY MOSS AND SLATER (REF. A-3)

These investigators reported tests of a powered 1/4-scale model of the LVTP-11, conducted at the University of Michigan in 1962. The tests were more limited in scope than the two investigations discussed above. No new general conclusions of significance were obtained. In one interesting test, alternate grousers in the track were removed, in order to see whether a reduction in interference between grousers would improve performance. The power increase required for this new configuration was about 50 percent. Trim by the bow was found to have a small beneficial effect. The highest value of propulsive coefficient obtained in these tests was 6.8 percent.

TESTS REPORTED BY PAVLICS (REF. A-4)

Pavlics reported the work conducted on an early-concept model of a variable-pitch paddle track at the U. S. Army Land Locomotion Laboratory in 1958.

A schematic drawing of the device is shown in Figure A-1. It was tested in a small water tank (Figure A-2). The lift and thrust generated, and the power absorbed by the partially submerged device for various rpm's and for various track angles relative to the water level, were measured. Tests were performed with two different blade sizes 6 x 3 and 4 x 3 inches; and with track angle settings of 30, 45 and 60 degrees. The track slip under all conditions was 100 percent, corresponding to bollard-pull operating conditions.

Lift, thrust, and horsepower were plotted against rpm. Maximum thrust obtained was approximately 20 lb per input horsepower. The tests indicated that the wider blades are more efficient. A comparison between this track and a 3/4-submerged "hydrofoil wheel" (cycloidal propeller), also tested at the Land Locomotion Laboratory,[A-7] was made. The paddle track is roughly 50 percent better than the hydrofoil wheel over the whole rpm-range covered.

Pavlics presented a calculation scheme for estimating the performance of the variable-pitch paddle track. This method makes use of lift and drag data for isolated plates, and utilizes the kinematics of the mechanism (Figure A-1) to ascertain relative velocities. While this calculation scheme ignores the effects of close spacing of grouser elements (relative to one another) on the lift and drag coefficients and on the flow to the elements, the numerical results agree reasonably well with the experiments for low values of rpm. This agreement should be viewed as fortuitous, in view of the great variance between the assumptions and the real nature of the flow, especially so because the results in the present paper show the effects of interactions between plates to be very large indeed.

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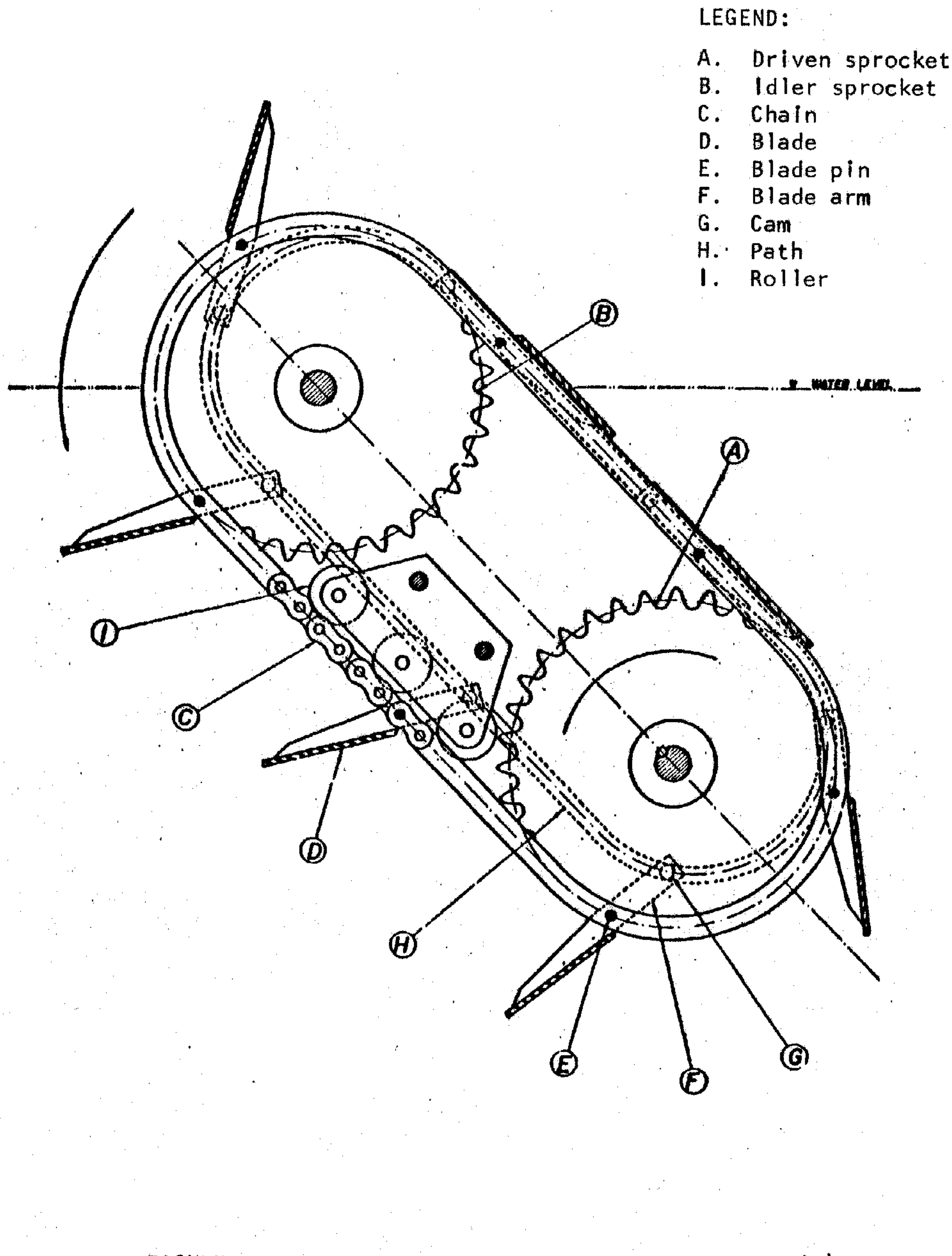
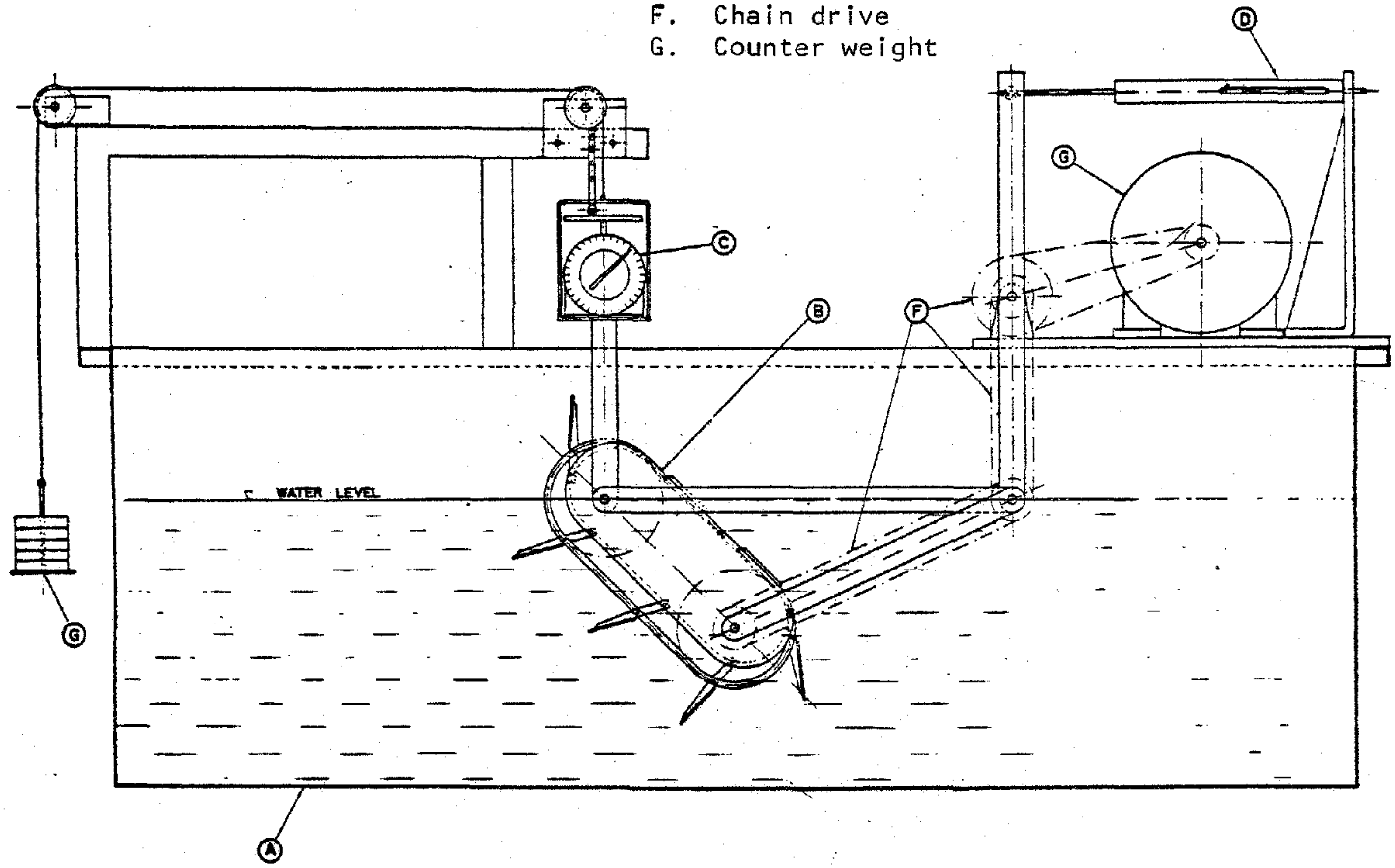


FIGURE A1. SCHEMATIC DRAWING OF THE PADDLE TRACK[A-4]

LEGEND:

A. Water tank
B. Paddle track
C. Gauge for measuring lift
D. Gauge for measuring thrust
E. Variable-speed motor
F. Chain drive
G. Counter weight



A-8

R-1136

FIGURE A2. SCHEMATIC DRAWING OF TEST APPARATUS WITH PADDLE TRACK

APPENDIX B

REVIEW OF LITERATURE ASSOCIATED WITH DRAG OF FLAT PLATES NORMAL TO A UNIFORM STREAM FLOW

Plates of Infinite Aspect Ratio

Classical theory of single-plate drag of infinite aspect ratio has been presented by Helmholz, Kirchhoff, and Rayleigh.[B-5] This is the method which uses the free-streamline notion. It assumes that the streamlines separate at both edges of the plate and extend to infinity downstream, and that the pressure in the bubble behind the plate is constant. The resultant equation is

$$C_D = \frac{D}{\frac{1}{2}\rho U^2 C} = \frac{2\pi}{\pi + 4} = 0.88$$

where
C_D = drag coefficient
D = drag
C = chord length
ρ = fluid density
U = fluid velocity

This value is roughly half of that obtained by experiment.

In order to improve the agreement between theory and experiment, various modifications to the above method have been tried by many researchers. Among them are Riabouchinsky and Gilbarg and Rock; Roshko's models should be mentioned.[B-1]

In the region where the Reynolds number is between 40 and approximately 1000, a strong occurrence of Karman vortex sheets is observed, and the resistance can be calculated by the following formula:

$$C_D = 4 \quad 2 \; \frac{h}{a} \left(\frac{a}{c}\right)^2 \frac{nc}{U} \left(1 - \frac{a}{c} \frac{nc}{U}\right)$$

where

- h = the spacing between two vortex sheets
- a = the spacing between two consecutive vortices in each sheet
- n = the number of vortices per unit time

This formula, however, gives a slightly smaller value than that obtained by experiment.[B-2]

There is an experimental study by Fage and Johansen, who measured the pressure distribution over a flat plate, with various angles of attack.[B-3] From integration of the pressure over the surface, they obtained the value 2.13 as the drag coefficient of the plate with a 90-degree angle of attack. This value is very high compared with the Helmholz-Kirchhoff-Rayleigh theory, but nearly coincides with the Karman value. They also studied the frequency at which vortices separate from the edges of the plate.

Flachsbart[B-4] also made an experimental study on the flow pattern around the plate, by smoke observation and the measurement of the drag. He obtained about 2.0 as the drag coefficient for the range of Reynolds number between 10^4 and 10^6.

In the case of an arbitrary angle of attack, there is a generalized Helmholz-Kirchhoff-Rayleigh formula for the normal force coefficient on a flat plate.[B-5]

$$C_N \equiv \frac{N}{\frac{1}{2}\rho U^2 C} = \frac{2\pi \sin \alpha}{4 + \pi \sin \alpha}$$

where N = the force normal to the plate surface

α = the angle of attack

For $\alpha = 90$ degrees , this equation reduces to that presented above.

Karman's vortices formula is also extended to the case of arbitrary angle of attack, with the insertion of $c \sin \alpha$ instead of c in the formula above.

Experiments by Fage and Johansen[B-3] show that the values obtained were usually pretty large compared with calculations from the theoretical formulas.

Plates of Finite Aspect Ratio

For the case of finite aspect ratio, the only theories presently available deal with axisymmetric cavity flows[B-1] which may be applicable to circular disks normal to the stream. Extensive measurements were made at Göttingen[B-6] for the flat plate with finite aspect ratio. The result is shown in Figure B-1.

Recently, Fail, Lawford, and Eyre[B-7] added other data on this problem. They made force measurements in a wind tunnel for various flat plates at a particular speed corresponding to a Reynolds number of the order of 10^5. Their result is also plotted in Figure B-1.

Plates in Tandem

There is no theory for the flow-pattern-around-multiple-plates system, except for the Riabouchinsky model mentioned above, which is considered to be the model for the front plate in the two-plates-in-tandem system, under special, limiting conditions.

There are also very few experimental studies. Eiffel conducted one experiment on the interference drag between two circular disks placed in tandem.[B-8] Some similarity exists between the disk and the rectangular flat plate. His result is shown in Figure B-2.

For the case of multiple plates arranged at arbitrary angle of attack and stagger, there are a considerable number of studies, both theoretical and experimental. However, these are usually related to a case of small angle of attack (such as the case of turbine compressor blades).

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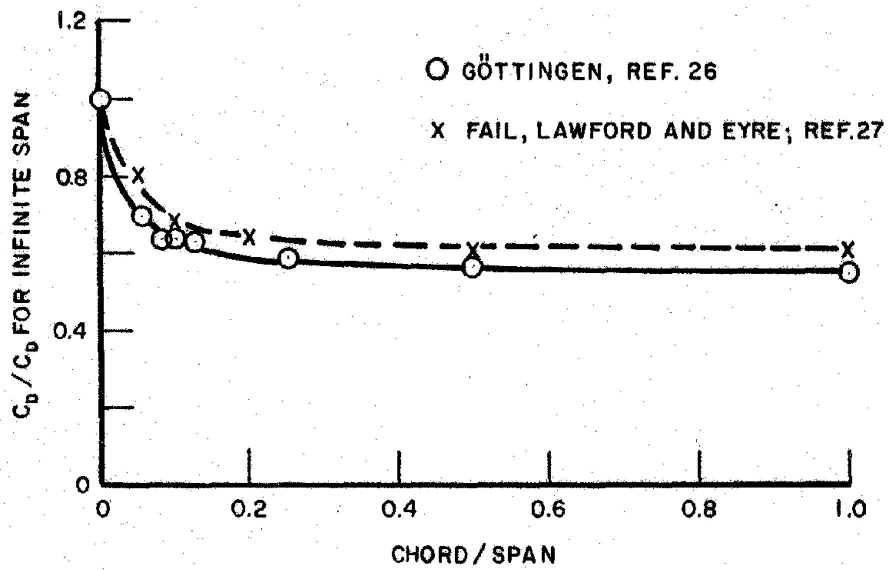

FIGURE B1. DRAG ON A FLAT PLATE

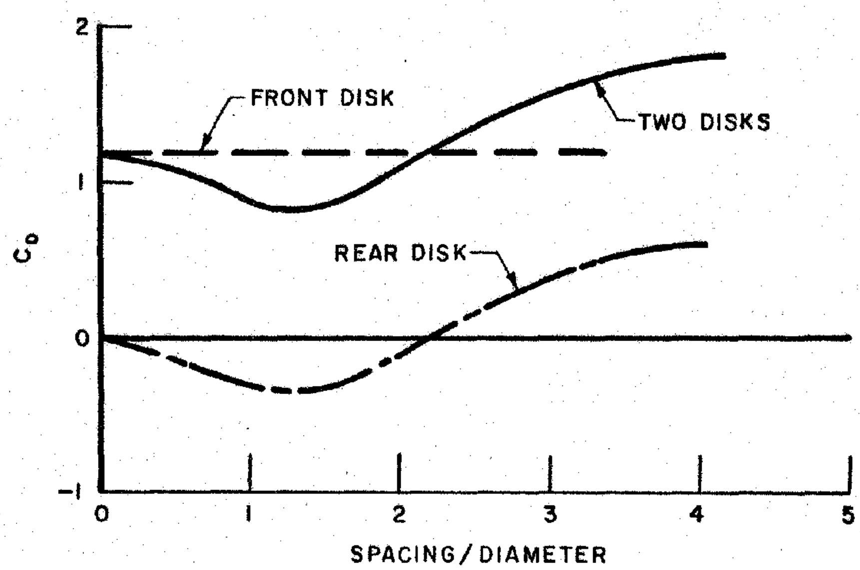

FIGURE B2. DRAG ON CIRCULAR DISKS IN TANDEM

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13. ABSTRACT

An investigation to improve the water propulsion performance of tracked vehicles is described. The study centers about drag measurements made in a wind tunnel and in a towing tank to investigate the effect of changing the shape and spacing of rectangular track plates.

It has been popularly believed that, due to turbulence, the first few track cleats do most of the propulsion. This investigation, however, establishes results indicating almost equal performance for all track cleats, throughout the length of the track.

Near-maximum plate thrust was obtained at spacing-to-plate-chord ratios above 6. Maximum thrust per unit length of track was obtained at a spacing-to-plate-chord ratio of approximately 1/2. Of the three rectangular-plate aspect ratios tested (2, 5, and 10), the aspect ratio of 10 gave the highest thrust per unit length.

Tests were made at plate centerline submergence-to-chord-width ratios of 2.54 and 4.57. No appreciable change in thrust was measured.

Summaries of previous studies associated with the problem of track propulsion are presented.

14. KEY WORDS	LINK A		LINK B		LINK C	
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Amphibians						
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